Development of Erosion Control Effectiveness Indices for Erosion Control Ditch Liners

Ontario

Ministry of Transportation

Research and Development Branch

Ontario
Ministry of Transportation
Research and Development Branch

Documentation Page

MAT-91-10

92-

Development of Erosion Control Effectiveness Indices for Erosion Control Ditch Liners

Author(s): S. Ahmed, T. Dickinson, S. Negi, R. Rudra, B. Slater
University of Guelph

Date Published: September, 1991

Published by: Research and Development Branch

Contact Person: Jack Armstrong, Materials Office
(416) 235- 5254

Abstract: Two forms of a mathematical model are presented as a basis for the estimation of rates of soil loss which can be expected in ditches with erosion control ditch liners. Both forms include the effective shear stress imposed by the water flow on the ditch boundary, and relate the stress to the ditch gradient and the depth of flow. Differences between the model forms result from different possible assumptions made for the functional relationship involving effective shear stress.

Preliminary experimental testing was conducted for validation and calibration of the models under laboratory conditions. Test results are presented for conditions involving bare soil and three selected ditch liners, and the results are compared with data available in the literature.

It is conlcuded that the forms of the mathematical model presented may well provide an excellent basis for ascertaining the relative effectiveness of ditch liners for erosion control. Field validation and calibration of the models are now required before one form or the other, or both forms, can be used for design purposes.

Comments: This study addresses the need and preliminary work in the development of a model to guide decision -making in the selection of the most cost-effective erosion control in ditches.

Key Words: erosion control, ditches, ditch liners, effective shear stress

Copyright Status: Crown copyright © 1991 Ministry of Transportation

00444/

MAT-91-10

Development of Erosion Control Effectiveness Indices for Erosion Control Ditch Liners

S. Ahmed
T. Dickinson
S. Negi
R. Rudra
B. Slater

School of Engineering
University of Guelph

Published by
The Research and Development Branch
Ontario Ministry of Transportation

Published without prejudice as to the application of the findings.
Crown copyright reserved; however, this document may be reproduced for non-commercial purposes with attribution to the Ministry.

For additional copies, contact:
The Editor, Technical Publications
Room 320, Central Building
1201 Wilson Avenue
Downsview, Ontario
Canada M3M 1J8

Telephone: (416) 235-3480
Fax: (416) 235-4872

September 1991

Table of Contents

1/ Introduction 1
2/ Objectives 2
3/ Model Development 2
3.1/ Fundamental Model Components 3
3.1.1/ Runoff Erosion 3
3.1.2/ Rainfall Erosion 4
3.2/ Tractive Shear Stress Expressions 4
3.3/ Proposed Models 8
4/ Experimental Design and Test Procedures 9
5/ Results and Discussion 12
5.1/ Summary of Results 21
6/ Conclusions and Recommendations 23
6.1/ Conclusions 23
6.2/ Recommendations 25
6.2.1/ Appropriate Validation 25
6.2.2/ Development of a Design Method 25
References 26
Appendix A - Laboratory Results 27
Appendix B - Sample Calculations (C-125 Liner) 29
Appendix C - RFP 1990/91 Work Plan Document 38

List of Tables and Figures

Tables

1/ Description of liners tested 10
2/ Summary of soil moisture content results 11
3/ Constants for initial form of model 22
4/ Constants for velocity relationships 22
5/ Constants for second form of model 22
6/ Models and maximum allowable flow depth equations 23

Figures

1/ Experimental results: model 1 12
2/ Erosion model for bare soil: model 1 13
3/ Erosion model for C-125 liner: model 1 13
4/ Erosion model for Eromat liner: model 1 14
5/ Maximum permissible flow depths: model 1 15
6/ Velocity vs hydraulic radius at 1% slope 16
7/ Velocity vs hydraulic radius at 3% slope 16
8/ Experimental results: model 2 17
9/ Erosion model for bare soil: model 2 18
10/ Erosion model for C-125 liner: model 2 18
11/ Erosion model for Eromat liner: model 2 19
12/ Maximum permissible flow depths: model 2 20
13/ Maximum permissible flow depths: models 1 and 2 20
14/ Maximum permissible flow rates: models 1 and 2 21

1/ Introduction

The problem has been identified in the RFP 1990/91 Work Plan Document, Reference 90075 (attached as Appendix C) as:

i) the lack of a standard approach to measure the effectiveness of erosion control ditch liners,

ii) the lack of a standard approach to measure the range of soil erosion susceptibility over which a given ditch erosion control product would be effective, and therefore,

iii) the lack of a sound basis for the selection of a ditch erosion control method for a particular set of conditions.

Countermeasures for erosion control, such as rock rip-rap and periodic revegetation, are not inexpensive and their application has, therefore, been limited to situations in which the benefits clearly outweigh the costs.

Other products including straw mats, mulches, natural fibres (eg. coconut fibres), synthetic polymers, or combinations of both natural and synthetic materials are marketed as ditch erosion control liners. Some of these products have been designed for use as liners for open channels and other conveyance systems although the majority of these materials were not developed specifically as ditch liners. Furthermore, there is not sufficient data available on performance characteristics of these products to confidently select liners for particular conditions.

The wide variety of products available and the lack of performance data has created a vital need for the development of a method of approach to evaluate the erosion control effectiveness of erosion control ditch liners.

2/ Objectives

The objective of this study has been established to be the development and preliminary testing of a mathematical model to estimate the rate of soil loss which can be expected in ditches protected by erosion control ditch liners. The model is to include important variables regarding ditch geometry and roughness, soil texture and erodibility, surface runoff rates and tractive forces, and ditch liner attributes. Consideration of various combinations of values for such variables will render the model useful for:

(i) estimation of the effectiveness of selected ditch liners for erosion control (relative to the situation with no liner),

(ii) estimation of the relative effectiveness of different ditch liners, and

(iii) estimation of the optimum range of applicability of selected ditch liners.

3/ Model Development

There are several modelling methods which have been used to estimate soil loss due to erosion in varying conditions. The method chosen to represent an erosion process must take into account the objectives of the model as well as the resources available for its verification and application.

Classical methods of modelling include the utilization of the Universal Soil Loss Equation (USLE) and its modifications (MUSLE, etc.). These approaches have been appropriate for the development of more complex models involving large areas for which extensive databases exist. This type of approach is not particularly suitable for the estimation of erosion in ditches.

Modelling methods used in the development of the interrill and rill erosion models, however, are appropriate for much smaller areas. These methods appear more suitable for the development of a model which will estimate erosion in ditches.

3.1/ Fundamental Model Components

Erosion in ditches is made up of two components: erosion due to rainfall and erosion due to overland runoff. The model suggested below accounts for these two components of soil loss separately.

3.1.1/ Runoff Erosion

The runoff component of soil erosion represents the soil loss due to concentrated flows. This soil loss has often been estimated through application of tractive force theory. According to this theory, the amount of erosion which occurs in a given channel condition varies with the shear stress applied by the flow. A flow transport model of rill erosion has been based upon the tractive force approach (Giorgini et.al., 1986). Also, Normann (1975) makes use of tractive force principles for the design of stable open channels. Obviously, this method is applicable over a wide range of concentrated flow conditions. Thus, a model involving the use of the tractive force method, appears well suited for representation of erosion due to flows in ditches.

A runoff component of erosion based on models used for the prediction of rill erosion takes the form,

$$E_{runoff} = \alpha \cdot (T_e - T_c)^{\beta} \qquad [1]$$

where,

- E_{runoff} is the erosion caused by concentrated flow,
- T_c is the critical tractive shear stress associated with the soil and cover or the liner and/or vegetation if present,
- T_e is the effective tractive shear stress of the flow,
- α is a coefficient possibly accounting for liner and soil differences, and
- β is a coefficient which may be a function of channel/ditch hydraulics.

3.1.2/ Rainfall Erosion

The rainfall erosion component represents soil loss due to the impact of raindrops on the soil surface. An equation similar to Meyer's equation (Foster et.al., 1977) can be used to represent the rainfall component of the model.

$$E_{rain} = C \cdot (I)^D \qquad [2]$$

where,

- E_{rain} is the erosion caused by impact of raindrops on the soil surface,
- I is storm intensity,
- C is a coefficient accounting for factors such as liner and land use, and
- D is a coefficient accounting for soil properties.

A combined model for erosion in ditches, including both rainfall and runoff components, could therefore be

$$E_{total} = E_{runoff} + E_{rain} \qquad [3]$$

Since the runoff component is considered likely to be the dominant one in most ditch erosion situations, only this component receives further attention in the subsequent development and testing phases of this report.

3.2/ Development of the Tractive Shear Stress Expressions

The rill erosion model requires a comparison of the relative magnitudes of critical and effective shear stresses. The critical shear stress is dependant on the soil type and the cover. It is the shear stress which is necessary to detach particles from the surface. Only a small amount of data are available concerning critical tractive shear stresses in bare soil conditions (Chow, 1959). Therefore, the determination of critical shear stress for channel conditions involving liners would require the collection of empirical data.

The effective shear stress developed by a concentrated flow condition is most commonly estimated using the equation

$$T_e = \gamma \cdot R \cdot S \qquad [4]$$

where,

T_e is the effective shear stress (N/m^3),

γ is the unit weight of water (N/m^2),

R is the hydraulic radius (m), and

S is the channel bed slope (m/m).

For wide channels, the hydraulic radius, R, is approximately equal to the depth of flow, y; and y can be substituted for R. This equation, when substituted into the tractive force model for erosion caused by concentrated flows, results in an expression of the form;

$$E_{runoff} = \alpha \cdot (\gamma \cdot y \cdot S - T_c)^{\beta} \qquad [5]$$

According to this model, significant erosion will begin to occur only when the effective shear stress of the flow has reached or exceeded the critical shear stress of the soil and/or cover. This implies that there is a critical point at which the effective shear stress is equal to the critical shear stress.

Now, it has been found that in wide channels, the velocity profile at the central and deepest section is the same regardless of channel shape (Normann, 1975). This finding, in conjunction with the above assumptions, implies that at a given slope, lining and soil type, there is a maximum flow depth above which the critical shear stress will be exceeded. Therefore, an equation relating maximum allowable flow depth to slope can be developed:

$$y_{max} = \frac{T_c}{\gamma \cdot S} \qquad [6]$$

where y_{max} is the maximum flow depth allowable to avoid erosive conditions.

This equation implies that maximum flow depth is proportional to the inverse of the slope, regardless of the constants in the tractive force erosion model (i.e. α and β in **[1]**). In other words, the slope of the relationship is governed by the equation defining effective shear stress.

Empirical data regarding a y_{max} versus S relationship (Normann, 1975) have suggested other than a simple inverse relationship. It appears that the powers in the relationship could range at least from S^{-1} to $S^{-0.5}$.

It should be noted that other assumptions have been made with respect to the estimation of the shear stress imposed on a surface by a concentrated fluid flow. The assumption that the force or stress resisting flow is proportional to the square of the average velocity was used in the development of the Chézy Formula for uniform flow (Chow, 1959). The equation has the form,

$$T_e = K \cdot V^2 \qquad [7]$$

where K is a constant of proportionality.

This relationship requires the use of a relationship for the average velocity of flow in a channel. Chézy's formula and Manning's equation (Chow, 1959) both relate the average flow velocity to the hydraulic radius and the slope of the channel bed. These equations are both of the form,

$$V = a \cdot R^b \cdot S^c \qquad [8]$$

where, a, b and c are constants for given channel and surface conditions. Substituting **[8]** into **[7]** results in an equation for the effective shear stress,

$$\tau_e = K \cdot a^2 \cdot R^{2b} \cdot S^{2c} \qquad [9]$$

Again, assuming the hydraulic radius can be considered equal to the flow depth, and substituting **[9]** into **[1]**,

$$E_{runoff} = \alpha \cdot (K \cdot a^2 \cdot y^{2b} \cdot S^{2c} - \tau_c)^{\beta} \qquad [10]$$

The values of a, b and c would have to be determined from empirical data comparing the velocity of flow to the hydraulic radius and the bed slope. Manning's equation is commonly used where a is 1/n, b is 2/3 and c is 1/2.

$$V = \left(\frac{1}{n}\right) \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}} \qquad [11]$$

The value n is the Manning's roughness of the surface.

The use of Manning's equation, then, would require estimation of the Manning's n values for each liner. It is important to note, as well, that McWhorter et. al. (1968) found that the Manning's roughness of most temporary ditch liners is a function of both hydraulic radius and slope. Thus, it may be necessary to develop more general relationships of the type in Equation **[8]** for each liner.

As for Equation **[5]**, Equation **[10]** implies there is a limiting effective shear stress beyond which erosion will occur. Also, as before, the effective shear stress is a function of the channel slope and the flow depth. Hence, at a given slope and channel condition, there will be a maximum depth beyond which erosion will occur. However, the relationship between maximum flow depth and channel slope now has the form,

$$y_{max} = \left[\frac{\tau_c}{K \cdot a^2}\right]^{\frac{1}{2b}} \cdot S^{-\frac{2c}{2b}} \qquad [12]$$

It is interesting to note that if, as in Chézy's formula, the velocity varies with the square root of both the slope and depth, Equation **[12]** is similar to Equation **[6]**.

Essentially, then, there are two approaches to calculating a limiting or maximum allowable shear stress, and associated maximum allowable depth. These approaches differ with regard to the basic assumptions regarding the manner in which shear stress is related to channel slope, depth or velocity. These assumptions each restrict the resulting models in their own way. The first assumption, that the shear stress can be equated to the component of the gravitational force parallel to the channel bed constrains the maximum allowable flow depth to be proportional to the inverse of the channel slope. The second assumption, that the shear stress is proportional to the square of the average velocity, constrains the maximum allowable flow depth to an expression involving the roughness relationship characteristic of each selected liner.

Information is not readily available to confidently choose one assumption over the other. Each assumption may be valid in a certain range of conditions. However, it is not apparent what these ranges may be. The analysis of the experimental results obtained during this project have been explored according to both methods in order to shed some light on the validity of the assumptions.

3.3/ Proposed Models

The general form of a runoff erosion model for flow in ditches has been selected to be,

$$E_{runoff} = \alpha \cdot (T_e - T_c)^{\beta} \qquad [13]$$

Two different assumptions can be made with respect to the calculation of the effective shear stress. These assumptions result in different forms of the final model.

i) From the assumption that effective shear stress is equal to a component of the gravitational force on the flow section:

$$E_{runoff} = \alpha \cdot (\gamma \cdot y \cdot S - T_c)^{\beta} \quad [14]$$

Given that the maximum allowable shear stress is T_c, the maximum allowable depth can be expressed as

$$y_{max} = \left[\frac{T_c}{\gamma}\right] \cdot S^{-1} \quad [15]$$

ii) From the assumption that effective shear stress is proportional to the square of the average velocity:

$$E_{runoff} = \alpha \cdot (K \cdot a^2 \cdot y^{2b} \cdot S^{2c} - T_c)^{\beta} \quad [16]$$

In this case, the maximum allowable depth is,

$$y_{max} = \left[\frac{T_c}{K \cdot a^2}\right]^{\left(\frac{1}{2b}\right)} \cdot S^{-\left(\frac{2c}{2b}\right)} \quad [17]$$

For each form of the model, a relationship can easily be developed which relates the maximum permissible flow depth to a maximum permissible flow rate for a given channel geometry.

Please Note: Calculations for the C-125 Liner can be found in Appendix B.

4/ Experimental Design and Test Procedures

Primary factors of interest in the study were liner type (surface condition), flowrate and bed slope. Effects of three types of liners, as described in Table 1, in addition to bare soil, two flowrates (1.43 l/s and 2.13 l/s), and slopes ranging from 1% to 16% were examined.

The test bed, or flume, dimensions were 1.50 m (length) by 0.30 m (width) by 0.10 m

Table 1 Description of liners tested.

	LINER	DESCRIPTION
(1)	P-300	consists of nylon fibres with heavy UV stabilized netting on the top and light UV stabilized netting on the bottom
(2)	C-125	consists of coconut fibre with a light non-photodegradable netting on both sides
(3)	EROMAT	consists of wheat straw which is attached to a single layer of photodegradable netting

(depth). The flume selected for this experiment had an adjustable bed slope which allowed selection of slopes ranging from 0% (horizontal) to 20% (20 m rise over 100 m run).

Tests were performed on a bed containing highly erodible silt loam soil (29.3% sand, 52.4% silt and 18.3% clay). The average depth of topsoil in the flume was 0.05 m (2"), and the remaining 0.05 m was occupied by a waterproof styrofoam which served as a base material for the soil. A styrofoam base was used because of the limited amount of soil available for tests.

Prior to experimentation, all available soil was sieved with no.4 mesh size which has an equivalent opening size of 4.76 mm. For each test run, approximately 26 kg of prepared soil was placed in the flume. The soil was pre-stressed using a roller and weights to achieve a bulk density close to field values. The bulk density of the prepared soil was 1.27 g/cm^3, compared to 1.34 g/cm^3 from site investigations (Asare et.al., 1990).

The mean volumetric water contents of the soil were measured to insure uniformity of initial conditions. The results from recorded soil moisture data are presented in Table 2.

Table 2 Summary of soil moisture content results.

SURFACE CONDITION	SOIL WATER CONTENT (m^3/m^3)		
	Initial	Before Test	After Test
Bare Soil	0.1732	0.2697	0.3845
P-300 Liner	0.0864	0.1829	0.3597
C-125 Liner	0.0970	0.1935	0.3739
EROMAT Liner	0.0939	0.1883	0.3296

The results contained in Table 2 indicate a disparity between the initial conditions of tests performed for each liner. This can be explained in terms of soil conditions before and after test. Initially, before the start of laboratory work, the soil had a high moisture content, but as time progressed and soil at the top of the heap was removed for testing the remaining soil became exposed, resulting in gradual drying due to circulating air.

Although the initial conditions might be slightly different for tests, the final water content indicates that soil was saturated at the conclusion of each run.

Water supply for the experiments consisted of three 1/3 horsepower electric pumps each attached by a flexible hose to one of three barrels with capacity of 200 litres. The average delivery rate of any single pump was 0.70 litres/second.

A 400 litre metallic reservoir was used for collection of sediment or eroded soil. Also, the length of all test runs was limited to three (3) minutes based on collection tank volume.

At the conclusion of each run, a sample of one litre was taken from the tank. Additionally, a sample of wet soil was taken from the flume bed to calculate the final soil moisture content for each test condition. To obtain sediment concentrations and moisture contents, all samples from the collection basin and flume were oven dried at 100° Celsius for a period of 24 hours. Weights of samples before and after testing were recorded.

5/ Results and Discussion

The runoff erosion models presented relate the amount of erosion occurring in a certain soil and cover condition to the depth of flow and the slope of the bed. To calibrate the model, the amount of erosion which occurred in each test run was compared to the flow depth and bed slope for the test. Initially, these comparisons are presented on the basis that the effective shear stress was equal to a component of the gravitational force. Then comparisons are made on the basis that shear stress varied with the square of the velocity. Finally, a comparison of the two sets of data is presented.

Figure 1 summarizes possible relationships between effective shear stress and amount of erosion for the four surface conditions considered. A small amount of erosion occurred in all tests regardless of the effective shear stress. It is thought that this initial erosion likely involved soil particles which were already detached from the surface. In the case of the bare soil, the C-125 liner and the Eromat liner, a shear stress condition was reached where a large amount of erosion suddenly began to occur. This result is

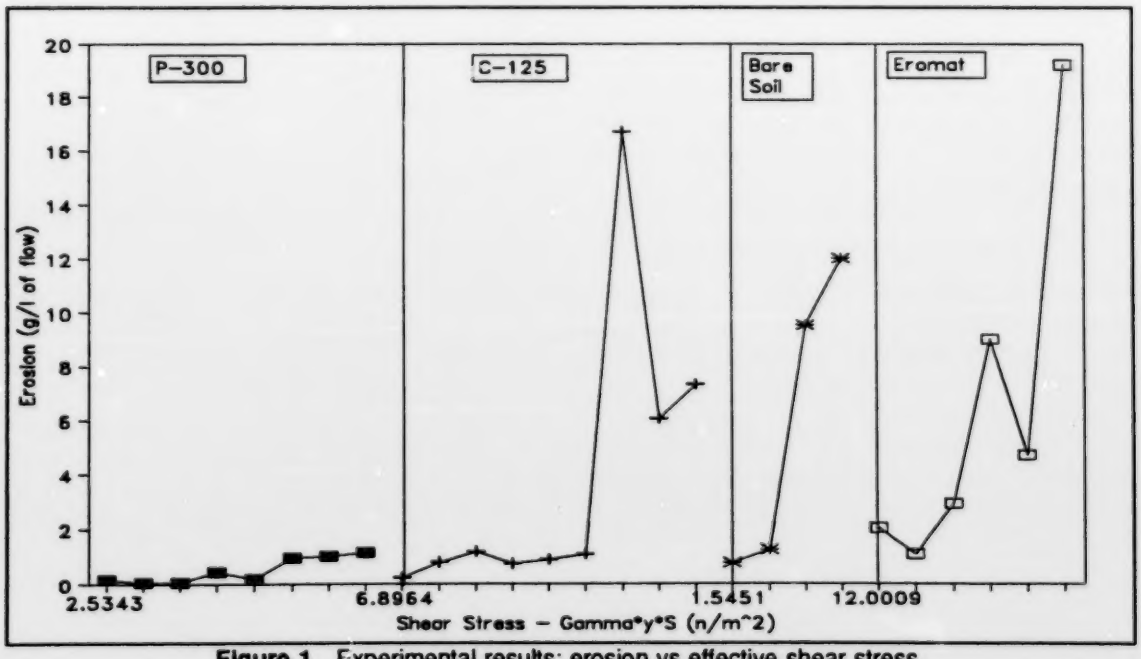

Figure 1 Experimental results: erosion vs effective shear stress.

consistent with the predictions of the model. The increase in erosion occurs after the critical shear stress is exceeded. The test on the P-300 liner never reached a point where the critical shear stress was exceeded.

For the three surface conditions on which a critical shear stress became evident, possible relationships were fit to the data. These equations are presented in Figures 2, 3 and 4.

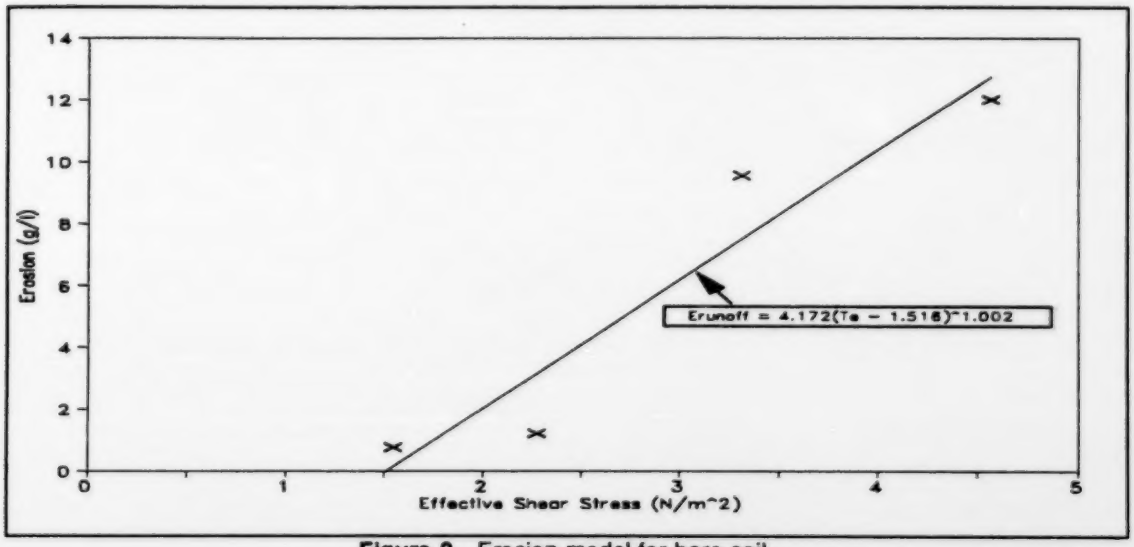

Figure 2 Erosion model for bare soil.

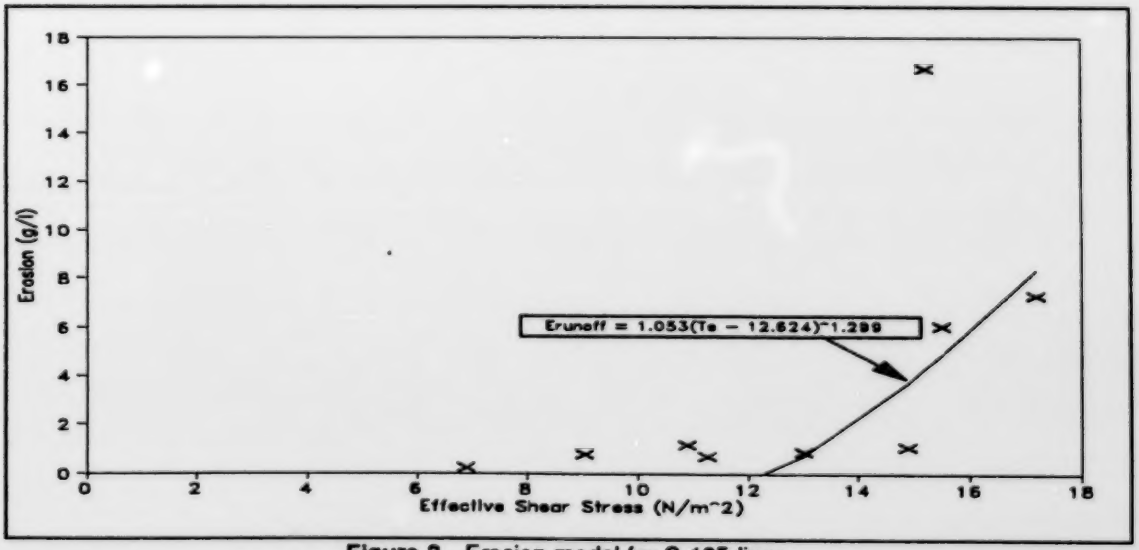

Figure 3 Erosion model for C-125 liner.

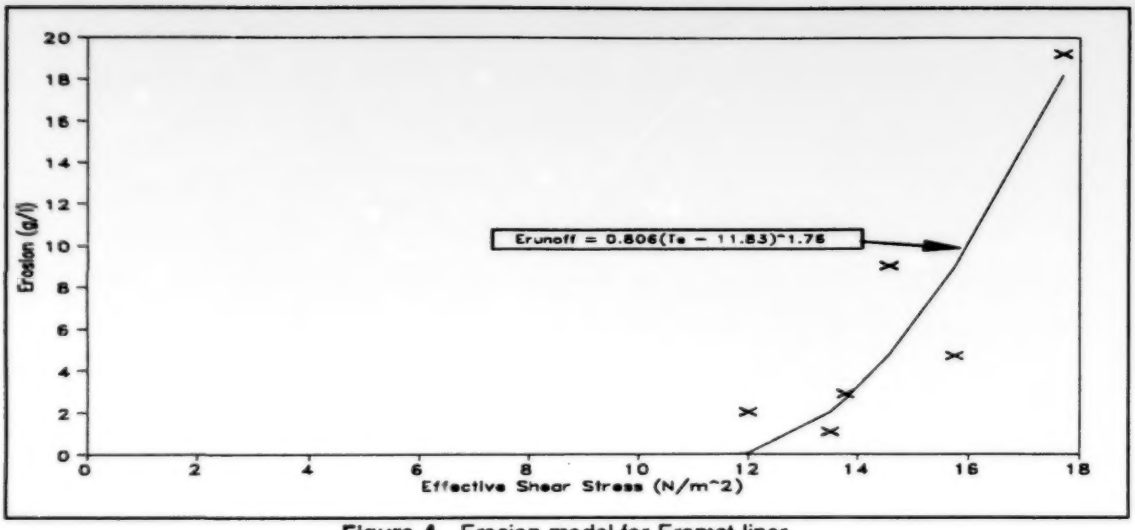

Figure 4 Erosion model for Eromat liner.

Empirical values for the critical shear stresses were estimated for all three surface conditions in which significant erosion occurred. The values obtained were 1.516, 12.624 and 11.83 N/m^2 for the bare soil, C-125 liner and Eromat liner respectively. Given these estimates, and the assumption that the effective shear stress is proportional to $\gamma y S$, a maximum permissible flow depth could be determined for each surface condition. That is,

$$y_{max} = \frac{T_c}{\gamma \cdot S} \qquad [18]$$

The maximum permissible flow depths for all surface conditions, as well as some maximum permissible depths determined by Normann (1975), are displayed in Figure 5.

As noted in the model development section, the equation used for calculation of the effective shear stress fixes the slope of the maximum permissible depth of flow lines in Figure 5 at -1. Normann's lines on the other hand are at a somewhat flatter gradient, having slopes in the range of -0.5 to -1. His empirical results suggest that it is worth exploring a definition different from $\gamma y S$ for effective shear stress.

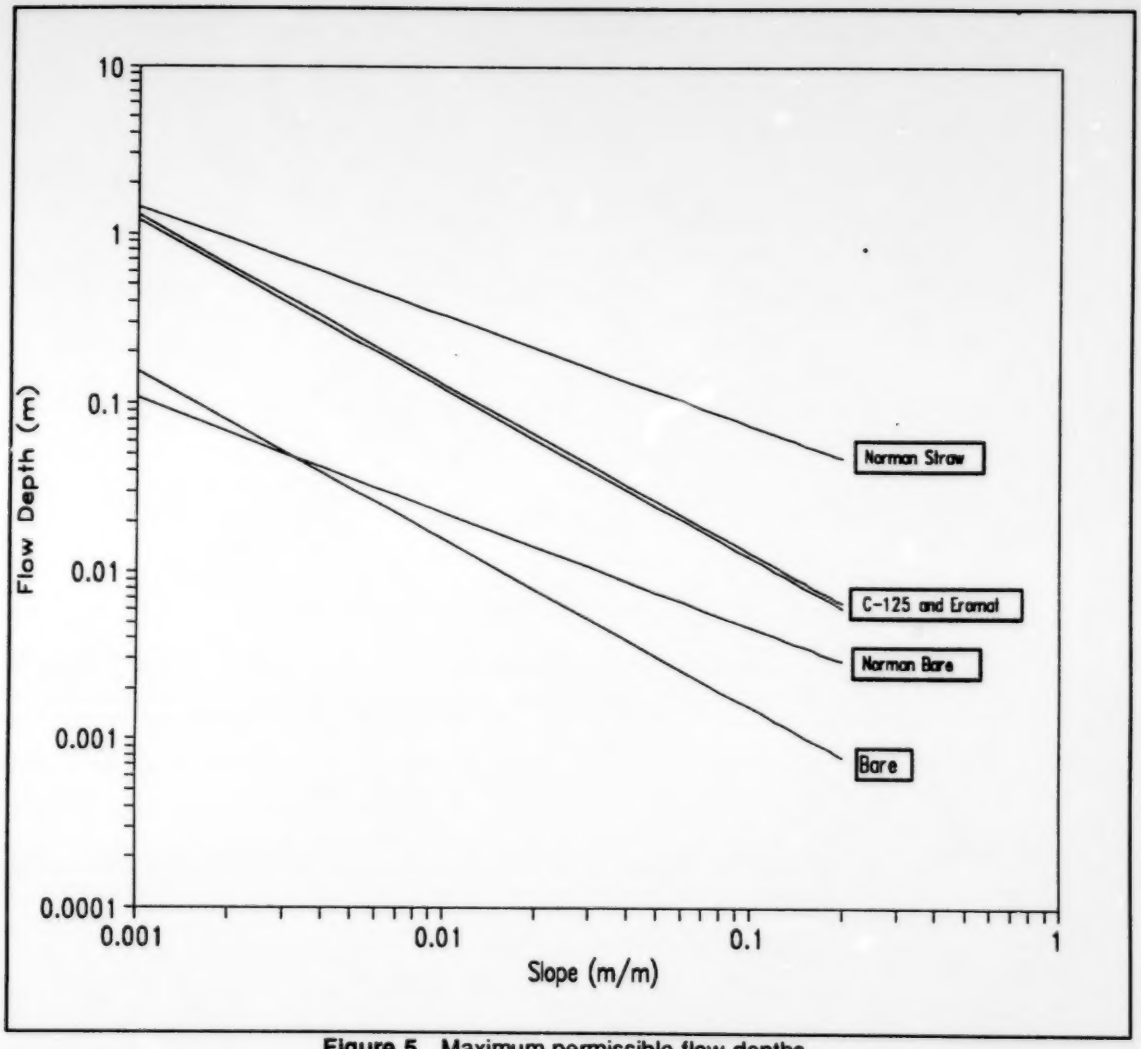

Figure 5 Maximum permissible flow depths.

A different shear stress equation can be developed using a relationship between average flow velocity, slope and hydraulic radius for each surface condition. The relationships, for all surface conditions, are presented in Figures 6 and 7 for 1% and 3% slopes, respectively. Note that the tests were carried out at only small depths. Hence, these relationships are valid only for small depths and hydraulic radii. Normann's relationship for bare soil is shown for comparative purposes.

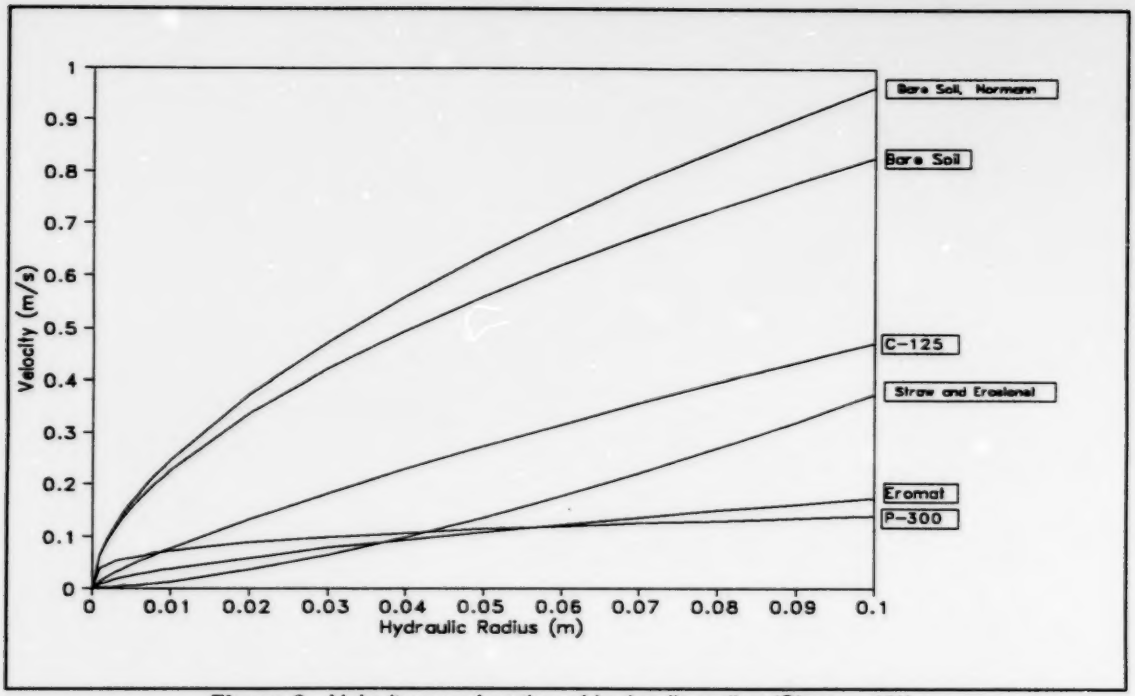

Figure 6 Velocity as a function of hydraulic radius (Slope = 1%).

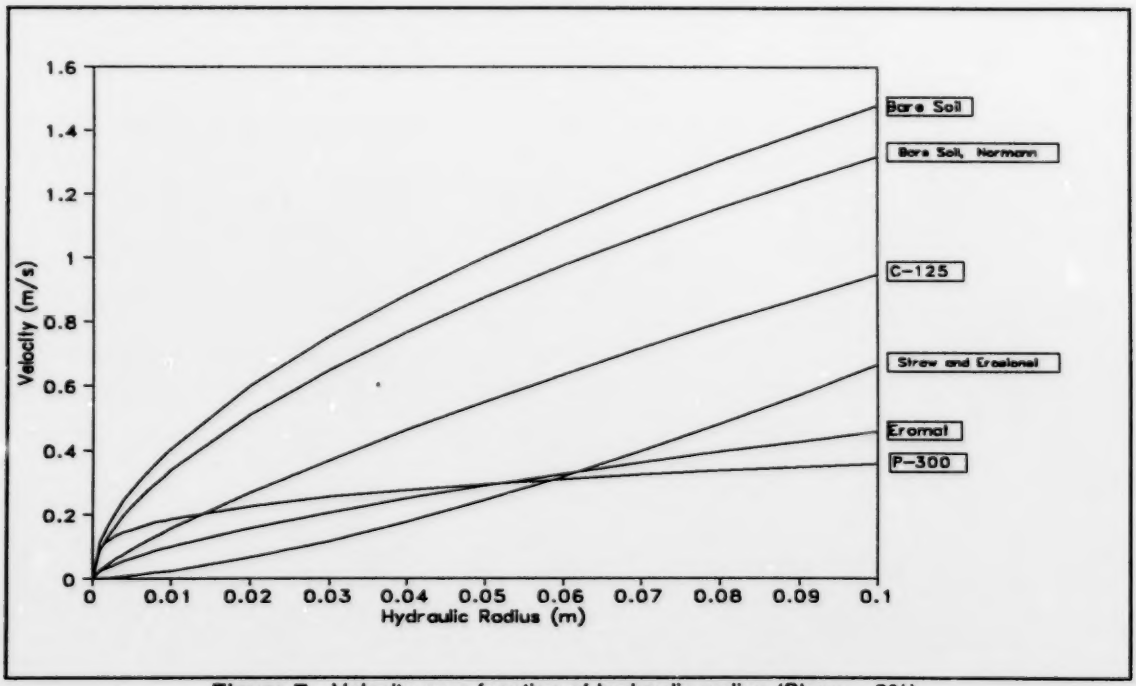

Figure 7 Velocity as a function of hydraulic radius (Slope = 3%).

Even though the database was sparse and the range of experimental conditions limited, these results are very similar to those obtained by Normann (1975).

The non-linear relationships for velocity as a function of hydraulic radius and slope were found to be as follows:

Bare Soil	$V = 39.3930 \cdot R^{0.5610} \cdot S^{0.5290}$
C-125 Liner	$V = 54.3503 \cdot R^{0.7837} \cdot S^{0.6398}$
Eromat Liner	$V = 47.4300 \cdot R^{0.6630} \cdot S^{0.8883}$
P-300 Liner	$V = 14.1395 \cdot R^{0.2839} \cdot S^{0.8623}$

Making use of the assumption that the shear stress could vary with the square of the velocity, the above relationships result in a different equation for the effective shear stress. The resulting model is of the form,

$$E = \alpha \cdot (K \cdot a^2 \cdot y^{2b} \cdot S^{2c} - T_c)^{\beta} \qquad [19]$$

The constant K, a proportionality constant from the shear stress equation, is unknown. As a result, the effective shear stress is also unknown. However, values for $y^{2b} \times S^{2c}$ are available from lab tests. Therefore, to determine the constants for the model, the erosion occurring in a test was compared to the value of $y^{2b} \times S^{2c}$. Results for all surface conditions are presented in Figure 8.

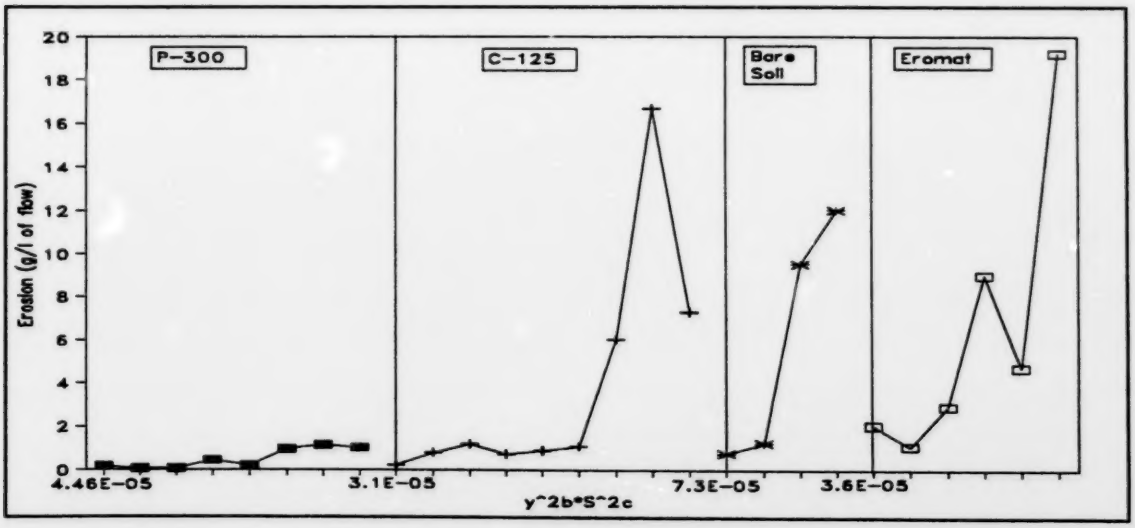

Figure 8 Erosion vs ($y^{2b} \times S^{2c}$).

As noted earlier, and as shown in Figure 8, the erosion which occurred with the P-300 liner was negligible. Therefore, that liner was again not considered in further calculations. Constants for the model, however, were determined for each of the other surface conditions. The resulting equations are presented and shown in Figures 9, 10 and 11 for bare soil, C-125 liner and Eromat liner, respectively.

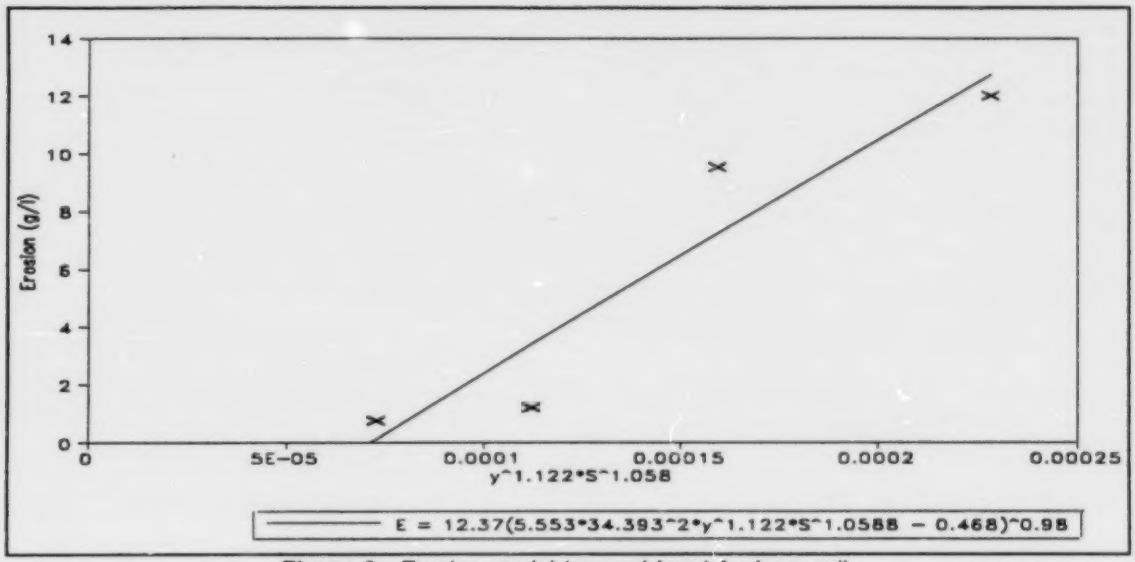

Figure 9 Erosion model (second form) for bare soil.

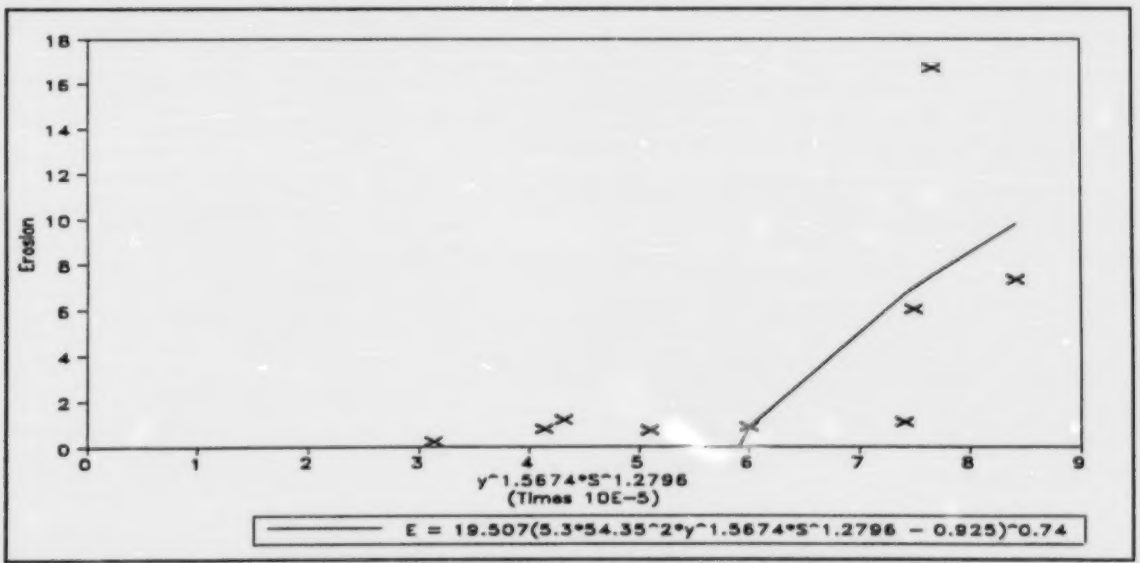

Figure 10 Erosion model (second form) for C-125 liner.

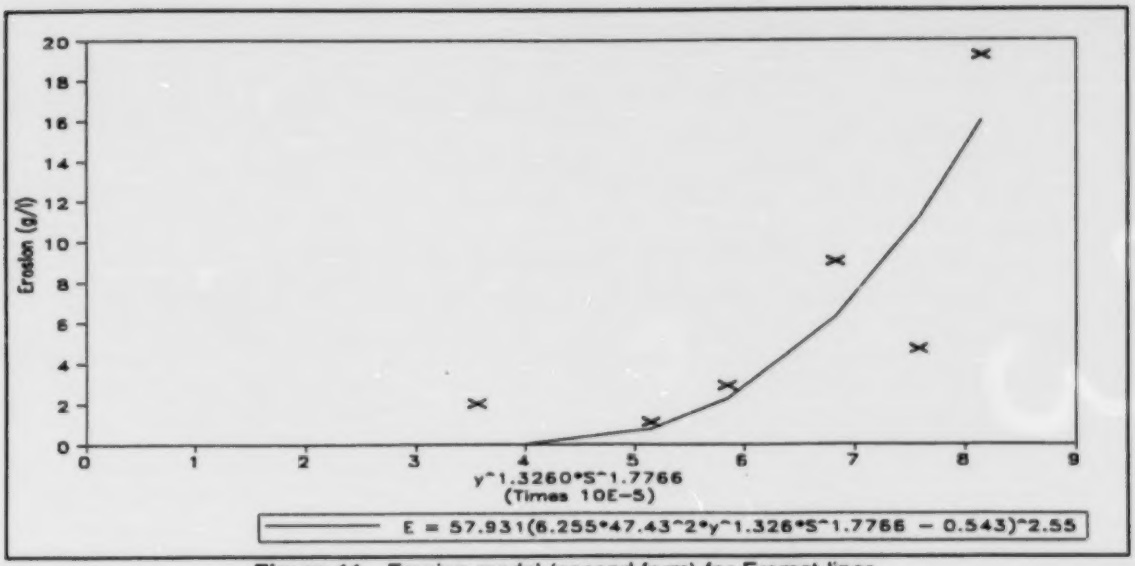

Figure 11 Erosion model (second form) for Eromat liner.

Maximum permissible depth of flow curves corresponding to the equations given in Figures 9, 10 and 11 are shown in Figure 12, along with Normann's relationships already presented in Figure 5. This second form of the model results in some maximum permissible flow depth curves which are quite similar to those presented by Normann. It also results in some curves which still differ in slope from his expected outcomes.

It is informative to compare the maximum permissible flow depths determined from the consideration of two possible definitions of effective shear stress with regard to the experimental data collected. These are presented together in Figure 13 for the bare soil, the C-125 liner and the Eromat liner.

The maximum permissible flow depth curves for the bare soil are very similar for both forms of the model. The curve for the C-125 liner has a much lower slope for the second form of the model. For the Eromat liner, the slope for the second form of the model is much higher. In all cases the magnitudes of the maximum permissible flow depths are similar for the range of bed slopes normally encountered in ditch design.

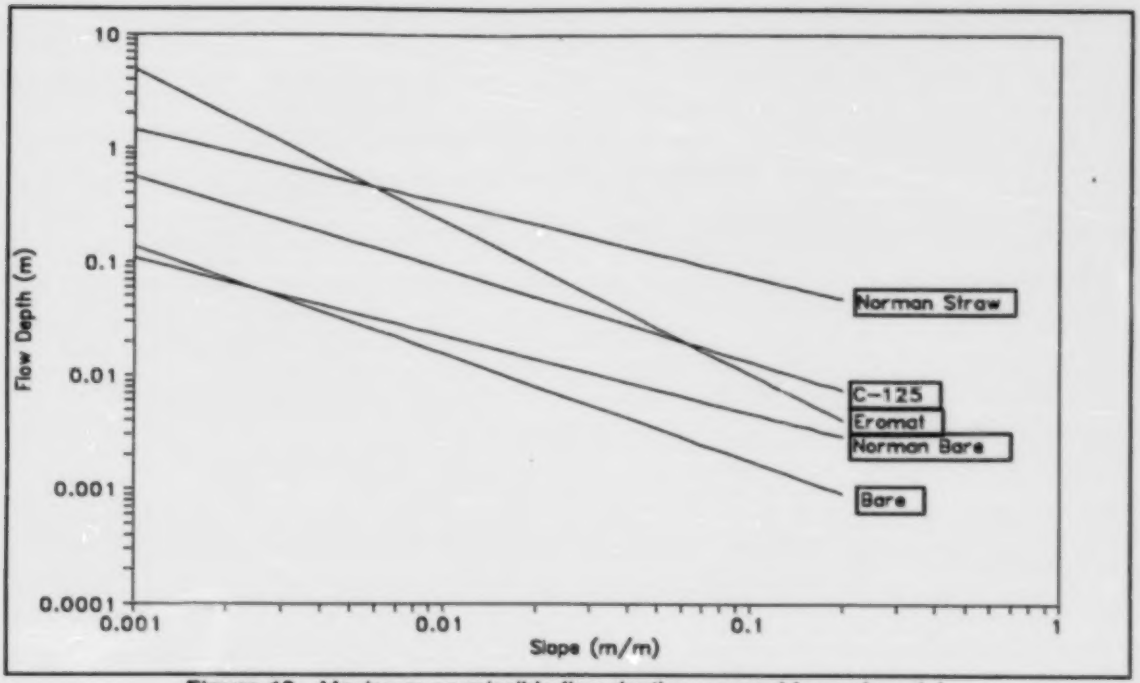

Figure 12 Maximum permissible flow depths - second form of model.

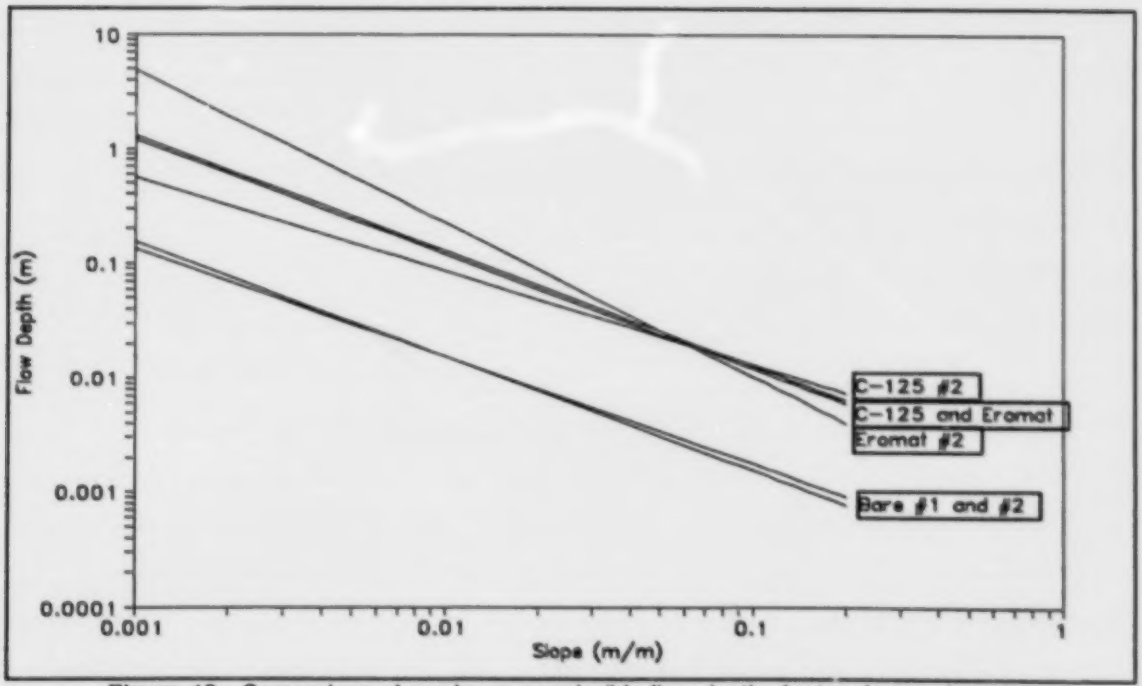

Figure 13 Comparison of maximum permissible flow depths for two forms of model.

Both forms of the model can be used to create equations for maximum permissible flow rate. This varies, of course, with the shape of the channel. Curves for maximum permissible flow rate are presented in Figure 14 for both model forms, for a trapezoidal channel with side slope of 4:1 and bottom width of 1 metre.

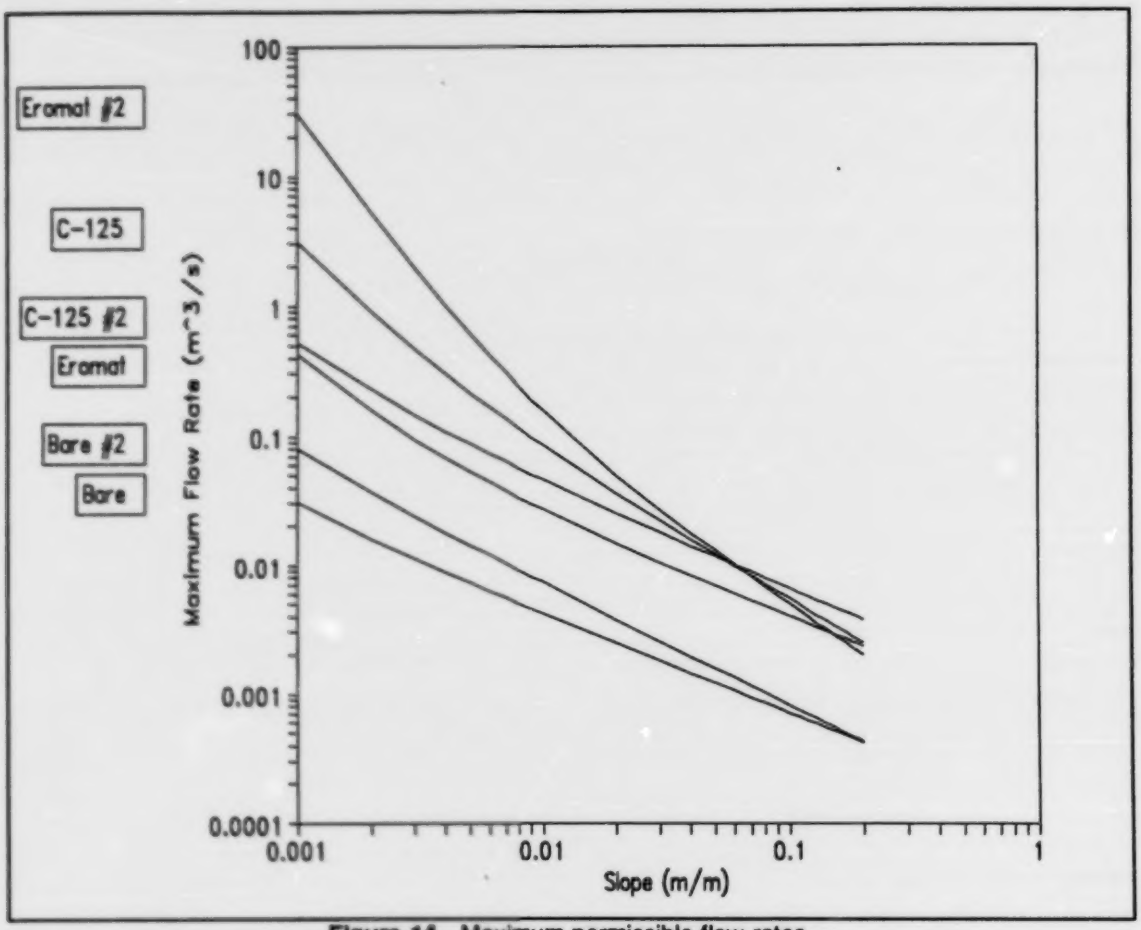

Figure 14 Maximum permissible flow rates.

5.1/ Summary of Results

The constants T_c, α and β for the model developed through the use of $T_e = \gamma y S$ are presented in Table 3 for the surface conditions under which significant erosion occurred.

Table 3 Constants for initial form of model

LINER	T_c	α	β
Bare Soil	1.516	4.172	1.002
C-125	12.624	1.053	1.298
EROMAT	11.83	0.806	1.76

The use of the relationship $T_e = KV^2$ requires an estimation of the average flow velocity. The constants a, b and c for the relationship between velocity, hydraulic radius and slope are presented in Table 4.

Table 4 Constants for velocity relationships.

LINER	a	b	c
Bare Soil	39.393	0.561	0.529
C-125	54.350	0.784	0.640
EROMAT	47.430	0.663	0.888

The constants T_c, K, α and β for the model which was developed through the use of the above relationships are shown in Table 5.

Table 5 Constants for second form of model.

LINER	T_c	K	α	β
Bare Soil	0.468	5.55	12.37	0.98
C-125	0.925	5.30	19.51	0.74
EROMAT	0.543	6.26	57.93	2.55

The model equations, as well as maximum allowable flow depth equations, for both model forms and all surface conditions are presented in Table 6.

Table 6 Model equations and maximum allowable flow depth equations.

LINER		EQUATION
Bare Soil	Model 1	$E_{runoff} = 4.172(\gamma y S - 1.516)^{1.002}$
	y_{max}	$y_{max} = 0.00015\ S^{-1}$
	Model 2	$E_{runoff}=12.37(6568.5\ y^{1.12}\ S^{1.06} - 0.45)^{0.98}$
	y_{max} 2	$y_{max} = 0.00016\ S^{-0.943}$
C-125	Model 1	$E_{runoff} = 1.053(\gamma y S - 12.624)^{1.298}$
	y_{max}	$y_{max} = 0.0013\ S^{-1}$
	Model 2	$E_{runoff}=19.51(15656\ y^{1.57}\ S^{1.28} - 0.93)^{0.74}$
	y_{max} 2	$y_{max} = 0.0022\ S^{-0.8164}$
EROMAT	Model 1	$E_{runoff} = 0.806(\gamma y S - 11.83)^{1.78}$
	y_{max}	$y_{max} = 0.0012\ S^{-1}$
	Model 2	$E_{runoff}=57.93(14071\ y^{1.33}\ S^{1.78} - 0.54)^{2.55}$
	y_{max} 2	$y_{max} = 0.00063\ S^{-1.340}$

Please refer to Appendix A for the actual test results.

6/ Conclusions and Recommendations

6.1/ Conclusions

The constants determined from the experimental results are believed to be applicable for the conditions tested; however, it is not yet possible to generalize these results. Also, applicability of the determined values is limited since only one type of soil was used, and a limited selection of liners were tested.

The results do, however, reveal that, for the conditions of the tests, the liners were all

effective in preventing erosion. Tests were unable to create any significant amount of erosion with the P-300 liner. Therefore, we can deduce that it provided the best protection, of the liners tested, against soil erosion. The apparent relative effectiveness of the C-125 and Eromat liners was dependant on the form of the model selected. It could be concluded that they have somewhat similar properties to reduce erosion. Unfortunately, the test conditions made it difficult to develop a specific form of the model for the P-300 liner.

There are inadequate results from experimentation to determine which assumption for the shear stress equation is valid in the laboratory conditions. However, both assumptions give similar results. A more accurate calculation of the effective shear stress would result in a better estimation of the maximum permissible flow depths and flow rates.

Tests carried out to determine the relationship between the average flow velocity and the hydraulic radius and bed slope are valid only at small depths. More extensive testing for this relationship may help in making a better estimate of the effective shear stress.

Example maximum allowable flow rates are presented along with the maximum allowable flow depths. It is worth noting that as the roughness of a liner increases, the flowrate at a given depth decreases. This occurs due to a decrease in the average velocity of flow. Liners which can withstand a high depth of flow may not be able to withstand high flow velocities and the resulting high flow rates. Therefore, presentation of the maximum flow rate for a variety of channels and surface conditions may be the most useful presentation of the model.

In summary, the three liners tested were effective in preventing erosion in the test conditions. The tests carried out seem to confirm the validity of the forms of the model selected. However, the constants determined from these tests can not be generalized to a wider range of conditions. More extensive testing will be necessary with other soil types, liners and conditions in order to develop final constants for the model.

6.2/ Recommendations

6.2.1/ Appropriate Validation

Further field (or laboratory) testing should be conducted for a range of conditions representative of roadside ditch situations. The preliminary testing undertaken during this project has validated the form of the model for ditch erosion. Further testing is required to ascertain parameter values for the model (i.e., calibrate the model) for various channel, liner and soil types.

Calibration of the ditch erosion model could involve two stages: an examination of MTO records, and field experiments. A review of anecdotal records in regional MTO offices regarding ditch liner failures and successes may provide very useful data points and reduce the need for more costly experimentation. The information required in this review should include estimates of the maximum flows and flow depths which have been carried effectively and/or have been erosive in selected ditches involving a range of soils, liners and channel gradients. For conditions not covered by historical records, field experiments should be conducted in existing and new ditch situations. These experiments could involve the provision of predesigned flows and flow depths to selected ditches (by means of a pumped supply), involving a range of soils, liners and gradients. The variables would be chosen to permit determination of conditions of incipient erosion.

6.2.2/ Development of a Design Method

Once the ditch erosion model has been calibrated, a method for the design of open channels involving flexible liners should be developed. A design approach based on maximum flowrate and depth have been presented in this report. Other presentation of the model, however, should be investigated, to achieve the most convenient design tool.

References

Asare, S., W.T. Dickinson, R.P. Rudra and G. Wall, 1990, Seasonal Variability of Hydraulic Conductivity, ASAE Paper 90-2022, Paper Presented in 1990 Summer Meeting of ASAE.

Barker, D.H., 1986, Biodegradable Geotextiles for Erosion Control and Slope Stabilisation, Civil Engineering (London), June, pp. 13-15.

Chow, V.T., 1959, *Open Channel Hydraulics*, McGraw-Hill, New York.

Dickinson, W.T. and A.M. Scott, 1979, Analysis of Streambank Erosion Variables, Canadian Agricultural Engineering, Vol. 21, pp. 19-25.

Dickinson, W.T., S.C. Negi and R.P. Rudra, 1990, Development of Erosion Control Effectiveness Indices for Erosion Control Ditch Liners (Proposal). 1990/91 Work Plan Development Document. School of Engineering, University of Guelph.

Foster, G.R., L.D. Meyer and C.A. Onstad, 1977, An Erosion Equation Derived from Basic Erosion Principles, Transactions ASAE, 1977, Vol 20, pp. 678-682.

Geotechnical Fabrics Report, 1989, 1990 Specifier's Guide, Geotechnical Fabrics Report, Industrial Fabrics Association International, Vol. 7, No. 7.

Giorgini, A., F. Zingales, A. Marani and J.W. Delleur, 1986, *Agricultural Non-Point Source Pollution: Model Selection and Application*, International Society for Ecological Modelling and Elsevier Science Publishing B.V.

Hanson, G.J., 1990, Surface Erodibility of Earthen Channels at High Stresses. Part I: Open Channel Testing, Transactions ASAE, Vol. 33, pp. 127-131.

MathCad, 1989, Mathsoft Inc.

McWhorter, J.C., T.G. Carperter and R.N. Clark, 1968, Erosion Control Criteria for Drainage Channels, Mississippi State University, State College, Mississippi.

Normann, J.M., 1975, Design of Stable Channels With Flexible Linings, United States Department of Transportation, Federal Highway Administration. Washington, D.C.

North American Green Inc, Technical Guide, North American Green Inc, Evansville, Indiana.

Appendix A
Laboratory Results

RESULTS FOR BARE SOIL

Date	Feb. 22	Feb. 22	Feb. 21	Feb. 21
Length (min)	3:00	3:00	3:01	3:05
Liner	None	None	None	None
Slope(%)	1	1	3	3
Flow Rate(l/s)	1.43	2.13	1.43	2.13
Tank Depth(cm)	41	53.5	40.2	54.5
Volume(l)	255.26	371.7	247.8	381.02
Sample Volume(l)	1	0.9	0.9	1
Total Mass(g)	317.95	281.51	298.4	345.86
Container(g)	317.2	280.41	289.81	333.85
Soil(g/l)	0.75	1.1	8.59	12.01
Total Soil(kg)	0.1914	0.4543	2.3652	4.576
Flow depth(m)	0.0158	0.0232	0.0113	0.0155

RESULTS FOR C-125

Date	Feb. 28	Feb. 27	Mar. 1	Feb. 28	Mar. 5	Mar. 5	Mar. 11	Mar. 18	Feb. 28
Length (min)	3:00	3:00	3:00	3:01	3:00	3:00	3:00	3:00	3:00
Liner	C-125	C-125	C-125	C-125	C-125	C-125	C-125	C-125	C-125
Slope(%)	3	5	8	10	12	12	10	14	10
Flow Rate(l/s)	2.13	2.13	2.13	1.43	1.43	2.13	2.13	2.13	2.13
Tank Depth(cm)	53.4	52.5	53.4	41.7	41	53	53	53.9	53.5
Volume(l)	370.77	362.39	370.77	261.78	255.26	367.04	367.04	375.43	371.7
Sample Volume(l)	1	1	1	1	1	1	1	1	1
Total Mass(g)	333.39	290.37	290.26	273.9	318.13	329.61	290.68	296.92	438.2
Container(g)	333.18	289.59	289.55	270.03	316.96	323.57	289.61	289.61	421.5
Soil(g/l)	0.21	0.78	0.71	0.87	1.17	6.04	1.07	7.31	16.7
Total Soil(kg)	0.0779	0.2827	0.2632	0.2277	0.2986	2.2169	0.3927	2.7444	6.2074
Flow depth(m)	0.0234	0.0184	0.0144	0.0133	0.009267	0.013183	0.015183	0.012517	0.0155

RESULTS FOR P-300

Date	Feb. 26	Feb. 26	Feb. 25	Feb. 26	Feb. 25	Mar. 4	Mar. 4	Mar. 5
Length (min)	3:00	3:00	3:02	3:03	3:00	3:00	3:00	3:00
Liner	P-300	P-300	P-300	P-300	P-300	P-300	P-300	P-300
Slope(%)	1	3	3	5	5	10	12	16
Flow Rate(l/s)	2.13	1.43	2.13	1.43	2.13	2.13	2.13	2.13
Tank Depth(cm)	53	40.6	52.3	40.6	53.5	53.5	52	52.2
Volume (l)	367.04	251.53	360.52	251.53	371.7	371.7	357.73	359.59
Sample Volume(l)	1	1	1	1	1	1	1	1
Total Mass(g)	317.34	280.47	333.91	324.15	289.99	290.5	334.08	273.9
Container(g)	317.2	280.41	333.85	323.73	289.81	289.55	332.96	272.9
Soil(g/l)	0.14	0.06	0.06	0.42	0.18	0.95	1.12	1
Total Soil(kg)	0.0514	0.0151	0.0216	0.1056	0.0669	0.3531	0.4007	0.3596
Flow depth(m)	0.0258	0.0199	0.0193	0.0144	0.016	0.0115	0.0115	0.007417

RESULTS FOR EROMAT

Date	Mar.6	Mar. 5	Mar. 11	Mar. 6	Mar. 6	Mar. 19	Mar. 18	Mar. 19
Length (min)	3:00	3:00	3:00	3:00	3:00	3:00	3:00	3:00
Liner	Ero-Mat	Ero-Mat	Ero-Mat	Ero-Mat	Ero-Mat	Ero-Mat	Ero-Mat	Ero-Mat
Slope(%)	5	8	12	10	10	10	12	12
Flow Rate(l/s)	2.13	2.13	2.13	2.13	1.43	2.13	1.43	2.13
Tank Depth(cm)	53	52.7	55.5	52.9	40	52.9	41.4	54.1
Volume (l)	367.04	364.25	390.33	366.11	245.94	366.11	258.98	377.29
Sample Volume(l)	1	1	1	1	1	1	1	1
Total Mass(g)	282.02	291.04	348.68	346.21	424.4	352.17	430.5	284.67
Container(g)	279.99	289.96	332.8	332.86	421.5	332.96	421.5	279.98
Soil(g/l)	2.03	1.08	15.88	13.35	2.9	19.21	9	4.69
Total Soil(kg)	0.7451	0.3934	6.1985	4.8876	0.7132	7.033	2.3308	1.7695
Flow depth(m)	0.0288	0.0215	0.0143	0.0178	0.0184	0.02235	0.0167	0.0177

Appendix B
Sample Calculations (C-125 Liner)

Sample Set of Data Analyses (C-125 Liner)

Please refer to Appendix A for the actual lab results for the C-125 liner.

The initial model has the form

$$E_{runoff} = \alpha \cdot (T_e - T_c)^{\beta} \qquad \text{[i]}$$

The model implies that there is a critical point at which the erosion will be equal to zero. This phenomenon should occur when the effective shear stress is equal to the critical shear stress of the surface. Unfortunately, due to laboratory conditions, the erosion is never zero. There is always a residual amount of erosion of free particles.

Initially, the effective shear stress was represented by the following equation.

$$T_e = \gamma \cdot y \cdot S \qquad \text{[ii]}$$

The depth of flow was measured at six positions along the flume. The average of the depth of flow at all six positions was used as the overall depth of flow for the test. Thus, the effective shear stress for each test could be calculated. The results of all nine tests carried out on the C-125 liner are shown as X's in Figure A.

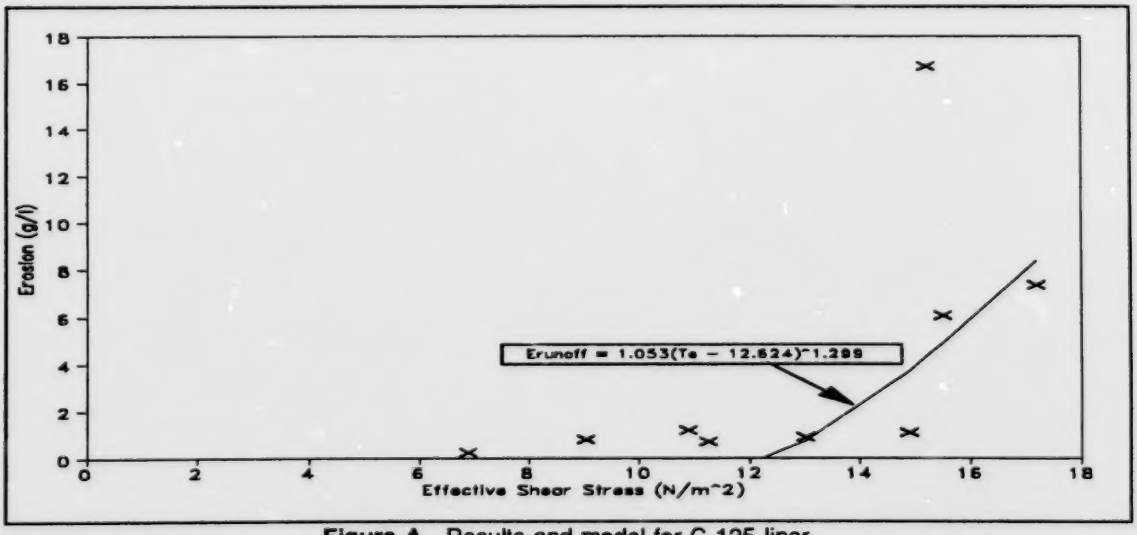

Figure A Results and model for C-125 liner.

These results are a good illustration of the expected outcome of the tests. There are two sections apparent for the resulting relationship between the effective shear stress and the amount of erosion. Residual erosion occurred until the effective shear stress approached 14 N/m^2. At this point, the amount of erosion began to increase rapidly. The model represents only the second part of this relationship. Therefore, constants for the model were developed using only the last five tests. In this case, one test seemed to be very inconsistent and was not considered in the model calibration.

The data was analyzed using non-linear least squares line fitting techniques. This was accomplished through the use of MathCAD (Mathsoft Inc., 1989). The resulting form of the model is,

$$E_{runoff} = 1.053(T_e - 12.624)^{1.299} \qquad \textbf{[iii]}$$

This model is shown in Figure A. The curve crosses the shear stress axis at the critical shear stress.

At critical conditions, the effective shear stress is equal to the critical shear stress. The critical shear stress is a constant associated with the soil type and cover. Comparison of the effective shear stress to the critical shear stress under critical conditions results in the following equation for the C-125 liner.

$$y_{max} = 0.0013 \cdot S^{-1} \qquad \textbf{[iv]}$$

y_{max} is the maximum depth of flow for a given slope. Flow depths greater than y_{max} will result in the critical shear stress for the surface being exceeded.

The relationship between maximum flow depth and bed slope is shown in Figure B. The relationship is restricted, by the shear stress Equation **[ii]**, to a simple inverse relationship. Literature shows that relationships with other slopes are common (Normann, 1975). A different basic assumption about the shear stress can be made.

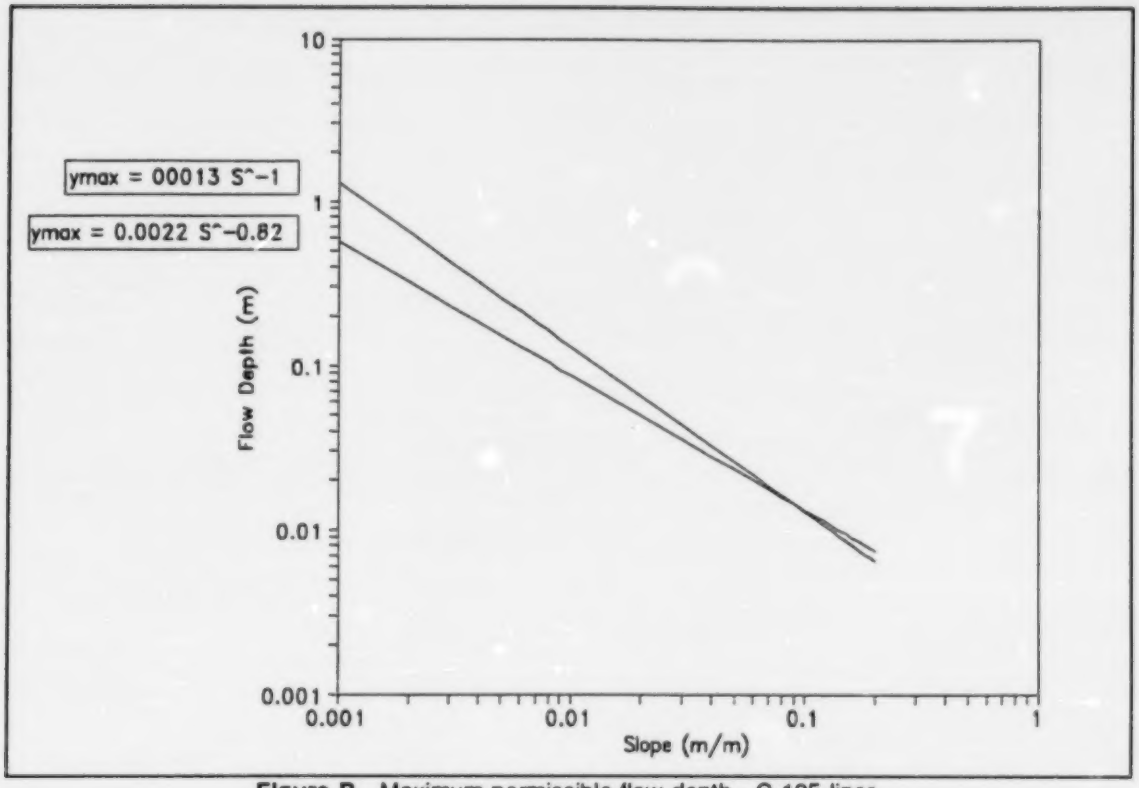

Figure B Maximum permissible flow depth - C-125 liner.

$$T_e \propto V^2 \qquad \text{[v]}$$

This requires a relationship for the average channel velocity.

$$V = a \cdot R^b \cdot S^c \qquad \text{[vi]}$$

Empirical data from the tests were used to develop the velocity relationships. At first, attempts were made to estimate the Manning's roughness coefficient (*n* in the following equation);

$$V = \left(\frac{1}{n}\right) \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}} \qquad \text{[vii]}$$

However, the results revealed that Manning's roughness coefficient is a function of both slope and hydraulic radius. This finding is confirmed by other literature (Normann, 1975). The data analysis method described earlier was used to develop a general equation (similar in form to **[vi]**) for the liner. The relationship between velocity and hydraulic radius is shown for slopes of 1%, 3% and 5% in Figure C.

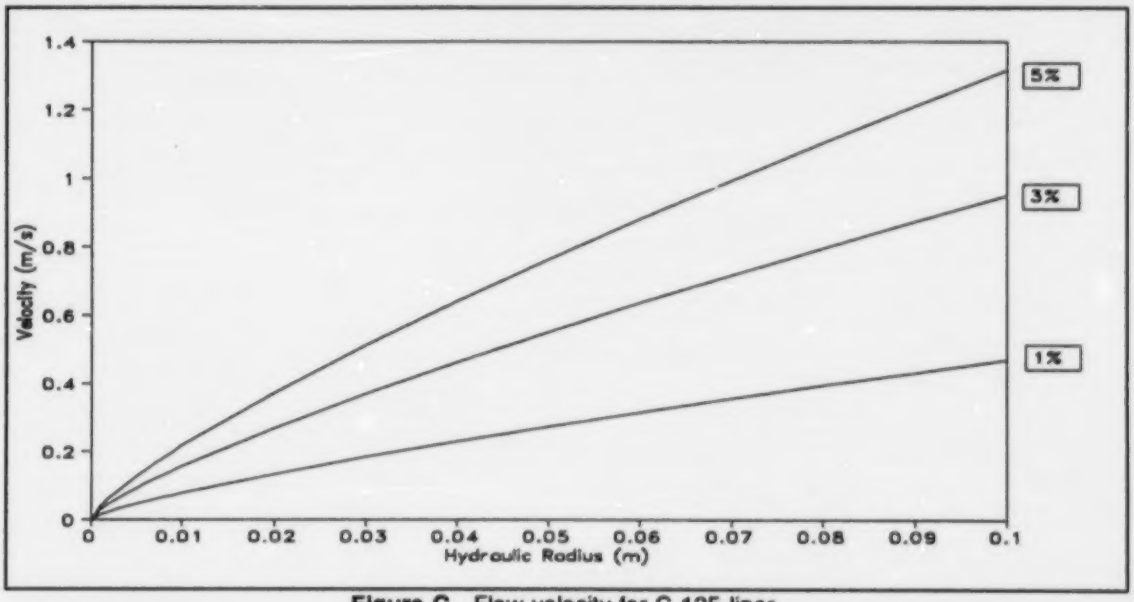

Figure C Flow velocity for C-125 liner.

The relationship is

$$V = 54.3503 \cdot R^{0.7837} \cdot S^{0.6396} \qquad \textbf{[viii]}$$

Equation **[viii]** can be substituted into Equation **[v]** to give the following relationship for the effective shear stress.

$$T_e = 2954.0 \cdot K \cdot y^{1.57} \cdot S^{1.28} \qquad \textbf{[ix]}$$

K is a constant of proportionality from the shear stress equation.

The resulting form of the model is

$$E = \alpha \cdot (2954.0 \cdot K \cdot y^{1.57} \cdot S^{1.28} - T_c)^{\beta} \qquad \textbf{[x]}$$

The erosion was set to zero and the effective shear stress was equated to the critical shear stress for critical conditions. This results in an equation for the maximum permissible flow depth.

$$y_{max} = \left[\frac{T_c}{2954.0 \cdot K}\right]^{\left(\frac{1}{2(0.7837)}\right)} \cdot S^{-\left(\frac{0.6398}{0.7837}\right)} \qquad \text{[xi]}$$

The effective shear stress cannot be calculated because the value of K is unknown. Therefore the results were reviewed in a graphical format by comparison of the value of $y^{1.57}*S^{1.28}$ to the amount of erosion. The results are presented in Figure D.

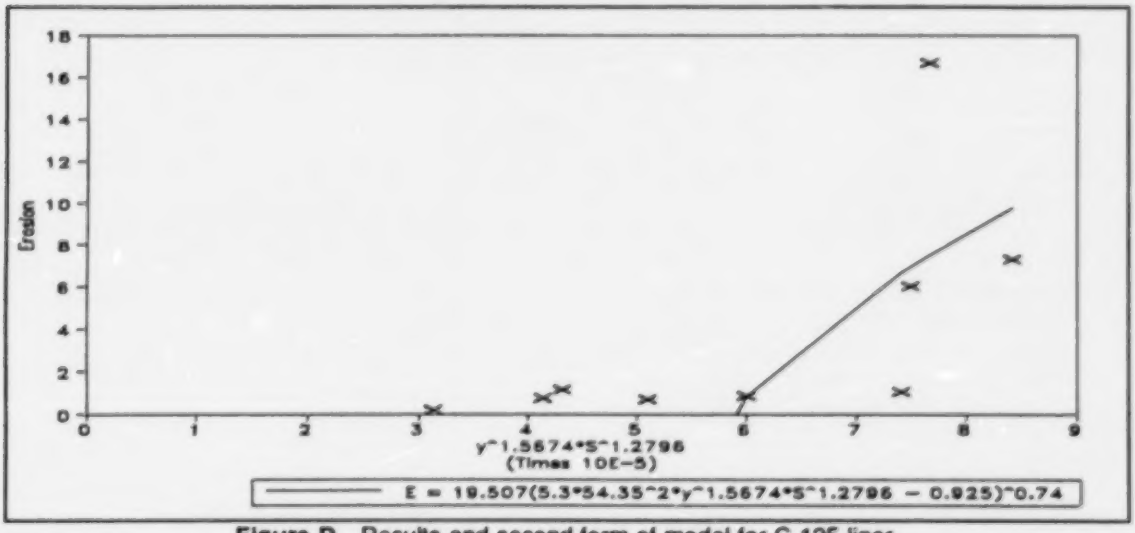

Figure D Results and second form of model for C-125 liner.

Again, there are two sections apparent for the resulting relationship between the effective shear stress and the amount of erosion. None of the tests appeared erratic in this case. Therefore, the last five tests were all used in the data analysis. In order to determine the value of the constant in the maximum permissible flow depth equation, the tests were all plotted as either squares or X's. The squares represent tests in which there was only residual erosion. The X's represent tests in which erosion was considered to have occurred. The value of the combined constant in the equation can be estimated

graphically. This procedure is shown in Figure E.

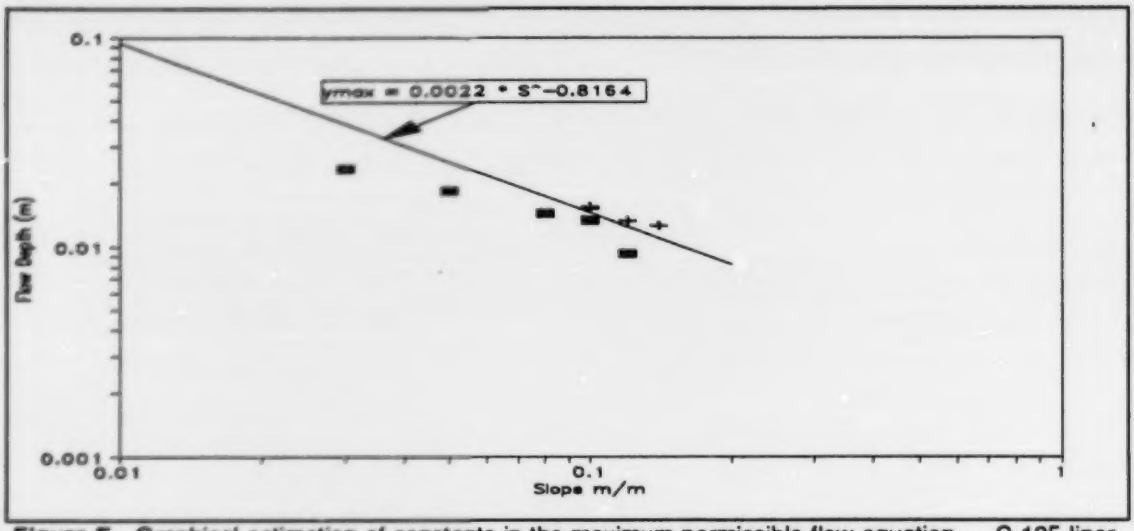

Figure E Graphical estimation of constants in the maximum permissible flow equation - C-125 liner.

The resulting equation for the maximum flow depth is

$$y_{max} = 0.0022 \cdot S^{-0.8164} \qquad \textbf{[xii]}$$

The value of the constant in the maximum permissible depth of flow Equation **[xii]** provides a relationship between the value of T_c and the constant K. This relationship aids in determination of the constants for the model. These were developed using the data analysis methods described earlier. The resulting model is shown in Figure D and in Equation **[xiii]**.

$$E = 19.51 \cdot (5.3 \times 2954.0 \cdot y^{1.57} \cdot S^{1.28} - T_c)^{0.74} \qquad \textbf{[xiii]}$$

The flowrate in a channel is the product of the average velocity and the channel area. By making use of Equation **[vi]**, this relationship becomes,

$$Q = A \cdot a \cdot R^b \cdot S^c \qquad \textbf{[xiv]}$$

where, A is the area of flow, m^2.

The flowrate is dependant on the channel shape. For any channel shape, the area can be determined as a function of the channel dimensions. For trapezoidal channels with a side slope of z metres of horizontal run per metre of rise, a bottom width of B metres, and a flow depth of y metres the area of the flow in the channel is given by

$$A = B \cdot y + z \cdot y^2 \qquad \textbf{[xv]}$$

The hydraulic radius can also be determined as a function of the same dimensions.

$$R = \frac{y \cdot (B + y \cdot z)}{B + 2 \cdot y \cdot \sqrt{1 + z^2}} \qquad \textbf{[xvi]}$$

The equations for the area and hydraulic radius, as well as the constants for the C-125 liner can be substituted into Equation **[xiv]**. This results in an equation for flow rate, which, for given channel dimensions, is a function of only slope and flow depth. The equations for maximum flow depth (**[iv]** and **[xii]**) can then be substituted into the equation. This results in an equation for the maximum permissible flow depth as a function of slope.

Using Equation **[iv]** as the maximum permissible flow depth equation results in the following relationship for the maximum permissible flow rate.

$$Q_{max} = 0.0013 \cdot S^{-1} \cdot (B + 0.0013 \cdot z \cdot S^{-1}) \cdot (54.35) \cdot \left(\frac{0.0013 \cdot S^{-1} \cdot (B + 0.0013 \cdot z \cdot S^{-1})}{B + 2 \cdot (0.0013) \cdot S^{-1} \sqrt{1 + z^2}} \right)^{0.78} \cdot S^{0.84} \qquad \textbf{[xvii]}$$

Using Equation **[xii]** as the maximum permissible flow depth equation results in the following relationship for the maximum permissible flow rate.

$$Q_{max} = 0.0022 \cdot S^{-0.82} \cdot (B + 0.0022 \cdot z \cdot S^{-0.82}) \cdot (54.35) \cdot \left(\frac{0.0022 \cdot S^{-0.82} \cdot (B + 0.0022 \cdot z \cdot S^{-0.82})}{B + 2 \cdot (0.0022) \cdot S^{-0.82} \sqrt{1 + z^2}} \right)^{0.78} \cdot S^{0.84} \qquad \textbf{[xviii]}$$

The maximum permissible flow rates for both forms of the model are shown in Figure F for a channel with a side slope of 4:1 and a bottom width of 1 m.

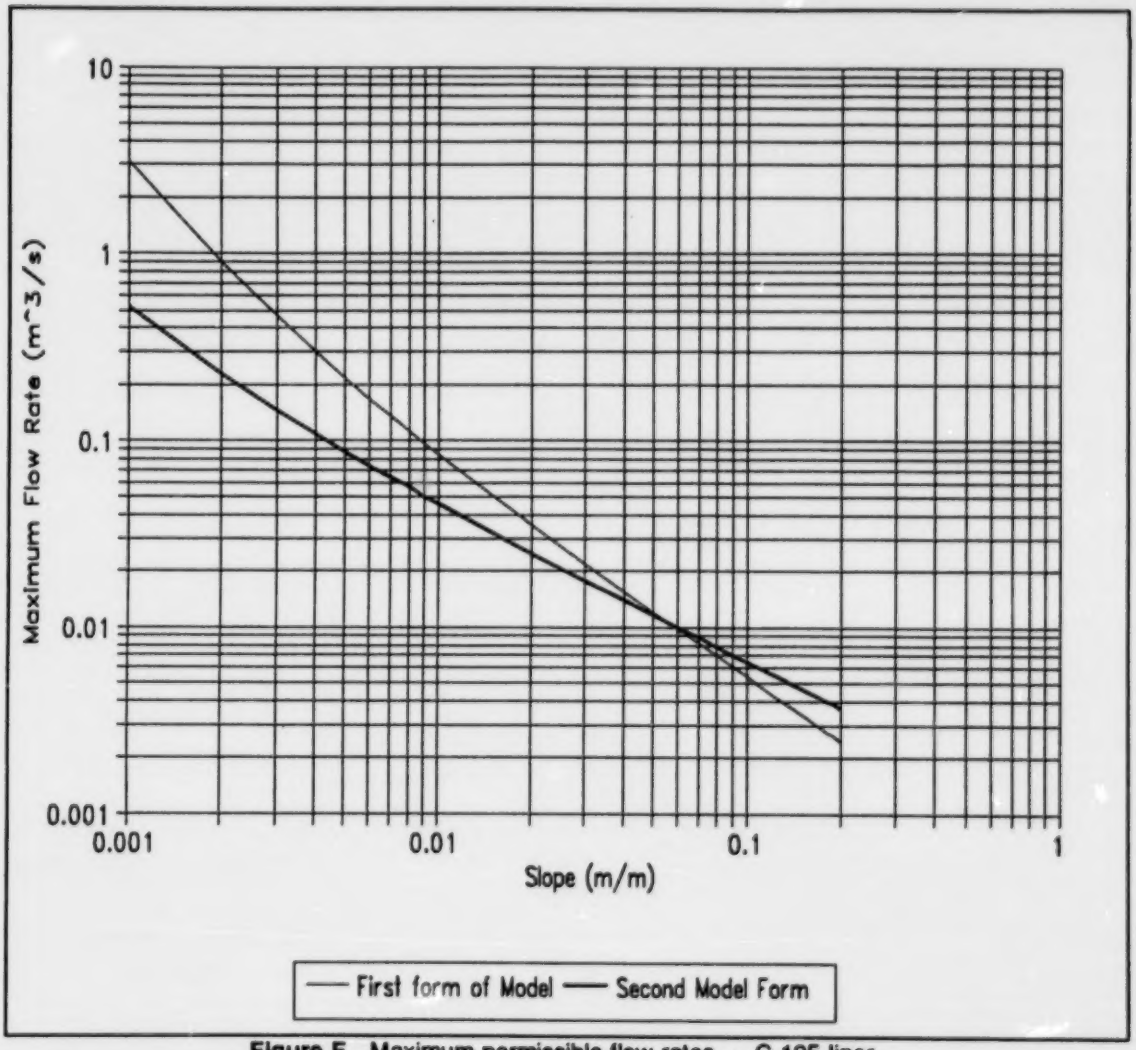

Figure F Maximum permissible flow rates - C-125 liner.

Appendix C

RFP 1990/91 Work Plan Document

(Re-Typed from Original)

Highway Engineering Division
Research and Development Branch

1990/91 WORK PLAN DEVELOPMENT DOCUMENT **Reference 90075**

REQUEST FOR PROPOSALS

TITLE: Development of erosion control effectiveness indices for erosion control ditch liners

PROBLEM:

There are many different products, design treatments and approaches available to the designer for application as ditch liners to reduce the incidence of erosion. There is, however, no standard approach to measure the effectiveness of these products, measures or approaches to a consistent manner so that they can be compared using the same parameters and measurement techniques.

There likewise is no standard approach used to measure the range of soil erosion susceptibility over which a given ditch erosion control liner product etc. would be effective. The Ministry has, however, proposed such an approach and is further examining the concept.

There is, therefore, no sound basis for the selection of a particular ditch erosion control method for a particular set of conditions. There is, therefore, a high potential for excessive soil erosion in ditches, especially where the erosion susceptibility is high, with consequent undesirable environmental impacts.

The problem is especially applicable in the development of the Designated Sources for Material List (DSM), a List of Ministry approved products for the use in a given application. While products are approved on the basis of a proven track record, information on the range of conditions over which they are effective is not one of the parameters used in the approval of ditch liners.

OBJECTIVES:

The objective is to derive a mathematical model that shows the relationship between the predicted amount or rate of soil eroded in a ditch relative to the actual amount or rate under the same conditions of soil type, runoff, ditch gradient, ditch shape, roughness and any other parameter which has an effect on erosion susceptibility and ditch liner effectiveness.

The application of the derived model must also be able to simulate the rates or amounts of eroded materials produced by varying the magnitude of the various parameters comprising the model. In this way it would be possible to use the model to predict the rate or amount of soil expected to be eroded in various designs, including those in which only the type of ditch liner changed.

One other potential application of the model would be the measurement of the range of erosion susceptibility over which the ditch liner was effective. Since it is expected that the index will be the slope of the plot of expected erosion against the predicted, any point of major deviation from linearity (assuming the relationship is linear) would represent the point on the erosion susceptibility

relationship where the liner was no longer effective. This information is vital in the development of an erosion control plan since there is no purpose in specifying or allowing the use of a product or approach etc. where it would be used beyond its capabilities.

POTENTIAL BENEFITS:

A sounder foundation for placing approved products on the DSM.

A sounder information base to be used in planning and design on the effectiveness and appropriateness of both proprietary and conventional design approaches for minimizing ditch erosion.

A greater degree of credibility by regulatory bodies and the Public especially in Environmental Assessment enquiries and interventions.

More efficient use of tax dollars for ditch erosion control by both the Ministry of Transportation, and municipalities on road construction/improvements.

Anticipated Costs: $15,000

Anticipation Duration: 1 year

Contact: J.J. Armstrong, 235-5254

Note: The field testing of the model will be contingent on the production of a usable model, the equipment available to the researcher, and the researcher's capability. Such testing will comprise a separate contract.